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LONG-LIFE MISSION RELIABILITY FOR OUTER PLANET ATMOSPHERIC ENTRY PROBES

by

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SUMMARY

The results of a critical literature analysis on the effects of prolonged exposure to deep space environment on the properties of outer planet atmospheric entry probe components are presented. Materials considered in this survey included elastomers and plastics, SBASI pyrotechnic devices, thermal control components, metal springs and electronic components. The rates of degradation of each component were determined and extrapolation techniques were used to predict the effects of exposure for up to 8 years to deep space. SBASI pyrotechnic devices were aged under accelerated conditions to an equivalent of 8 years in space and functionally tested. Results of the literature analysis of the selected components and testing of the SBASI devices indicated that no severe degradation should be expected during an 8-year space mission.

INTRODUCTION

A goal of planetary scientists is a systematic survey of the outer planets by a combination of flyby, orbiter and atmospheric entry probe missions. To accomplish such an ambitious scientific objective, probe components must maintain functional capabilities during prolonged exposure to deep-space environment.

The primary objective of this program has been, therefore, to identify, through a critical literature survey, the chemical and physical changes resulting from the exposure of selected probe components to the space environment and thereby, to identify the rates of those processes which result in degradation of useful properties.

This investigation centered on an examination of elastomers and plastics, thermal control components, electronic devices, metal springs and SBASI pyrotechnic devices. The primary environmental factor of interest was the high vacuum of deep space.

TECHNICAL APPROACH

Materials Selection

The materials considered in this program were selected by a review of projected probe design and in conjunction with NASA ARC personnel. The materials and their function are listed below with their critical properties.

TABLE I

MATERIAL SELECTION

Material	Function	Property
Elastomers Viton Silicone Teflon Vespel	Seals, O-rings Potting, Gaskets	Ductility, Elongation, Set, Porosity
Thermal Control Phenolic Polyurethane MLI Blanket	Thermal Control	Thermal Conductivity α/ϵ
Pyrotechnic Devices	Initiators	Peak Pressure, Ignition Delay, Time to Peak Pressure
Metal Springs	Probe-Separation Instrument Deployment	Force Constant Relaxation
Electronic Devices	Timers, Switches, etc.	Various*

*The specific properties of the electronic devices vary with design and function. The focus of activities in this area centered upon long-term reliability.

Definition of Environment

A proper evaluation of reliability of materials to be used in the outer planet atmospheric entry probe begins with a determination of the environment in which they must operate. Excluding cosmic radiations and micrometeorites, the more important factors characterizing the space environment are (1) vacuum and thermal-vacuum, (2) ultraviolet radiation, and (3) particle radiation. As the probe will be shielded from the sun during most of the time in transit, it is expected that radiation damage during transit will be minimal. The survey conducted during this program has, therefore, been primarily concentrated on the effects of thermal-vacuum on probe materials.

The range of gas pressures encountered with increasing altitude is shown in Table II.

TABLE II
PRESSURE OF SPACE[1]

Altitude	Pressure mm Hg	Composition
Sea Level	760	N_2, O_2, Ar
30 km	90	N_2, O_2, Ar
200 km	10^{-6}	N_2, O, O_2, O^+
800 km	10^{-9}	O, O^+, H
6500 km	10^{-12}	H^+, H
> 22, 000 km	$< 10^{-12}$	H^+, He^{++}

The pressure falls from 760 torr at sea level to less than 10^{-12} torr beyond 6500 km.

Although approximate temperatures are known of the gas in space, these temperatures have little effect on the internal temperature of a spacecraft. The temperature of the probe will be controlled by the use of radioisotope heaters, by conduction and radiation through the probe structure, and by an external insulation blanket. Preliminary design configurations have resulted in projected internal temperatures of ambient or below. For the purposes of this study it has been assumed that components will be exposed to a temperature of 25°C at high vacuum for periods up to 8 years.

Method of Analysis

Throughout this program we have surveyed the literature concerning the rate of deterioration of materials of interest under environmental conditions similar to those to be experienced during transit of the probe -- i.e., high vacuum at near ambient temperatures. Little information was available for such temperatures, however, because measuring low-temperature decomposition in a convenient real-time scale is usually difficult or impossible. The approach taken in most studies surveyed in this program has been to study degradation processes at elevated temperatures.

It has long been recognized that the relation of temperature to the rate of a chemical process can be determined by the Arrhenius expression

$$k = Ae^{-E/RT}$$

where k is the rate constant for decomposition, E is the activation energy in kcal/mole, T is the absolute temperature, and A is an experimentally determined frequency factor.

If the rate constant (k_{T_1}) and activation energy are known at some elevated temperature (T_1), the rate constant (k_{T_2}) can be calculated at any lower temperature (T_2) as shown in the following derivation:

$$k_{T_1} = Ae^{-E/RT_1}$$

$$k_{T_2} = Ae^{-E/RT_2}$$

$$\frac{k_{T_1}}{k_{T_2}} = e^{\frac{E}{RT_2} - \frac{E}{RT_1}}$$

$$\frac{k_{T_1}}{k_{T_2}} = e^{\frac{E}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)}$$

In those cases where data have been obtained at elevated temperatures, rates have been extrapolated to lower temperatures by the above procedure. For simplicity, all data have been extrapolated to 25°C, although this is slightly higher than average temperatures expected within the probe(2).

Indiscriminate use of this approach to calculate aging rates can lead to erroneous conclusions, in that elevated temperatures can often cause extraneous high-temperature reactions, side reactions, or altered gas phase mass transfer to occur -- i. e., phenomena which are in no way related to aging at lower temperatures. This kind of reaction is shown schematically in Fig. 1.

Reaction A is one that steadily and moderately increases in rate with increase in temperature. Reaction B, on the other hand, has a very high activation energy. Within the range of 25°C and somewhat above, its rate is insignificant; however, at somewhat higher temperatures, its rate becomes important. It is obvious that data collected at elevated temperatures and

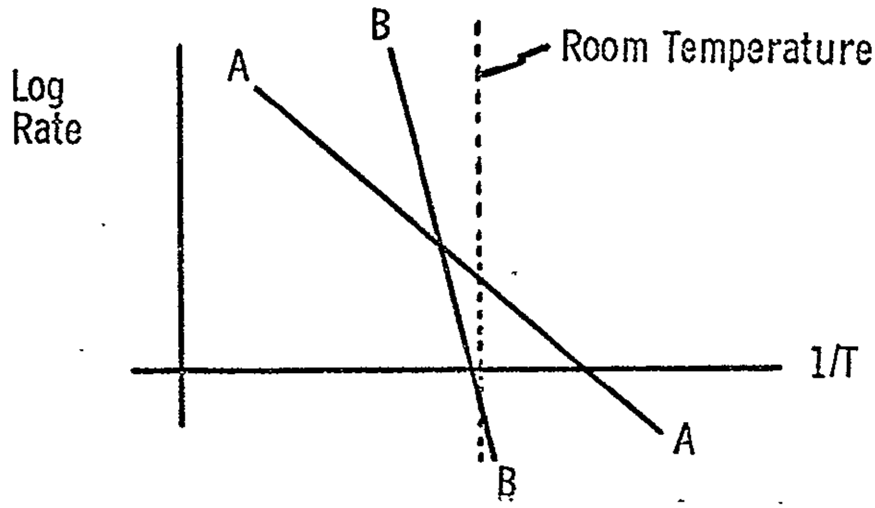

Fig. 1. Arrhenius Plot Illustrating Change in Reaction Mechanism with Temperature

extrapolated to temperatures near 25^{o}C would greatly underestimate degradative rates.

Of course, not all reactions are expected to be of this type. Some will be similar to reaction A -- important over a wide temperature range. Others, which have a high activation energy (e. g., reaction B), will be important at room temperature, because curve B has an intercept on the 1/T axis at room temperature. It is extremely important, therefore, that if elevated temperature data are to be used for calculating aging phenomena, such data must be within the temperature range applicable to the chemical reaction occurring in real-time aging.

The problems in calculating reliable aging data are generally more severe when spacecraft components are exposed to a variable or composite environment. For example, a plastic component used in a land-based system may degrade by auto-oxidation at ambient temperatures, by pyrolysis or thermal degradation at elevated temperatures, by reactions with pollutants or water vapor if located in specific areas, or by reactions

with solvents or cleaning fluids. In such cases, predictions of aging behavior from elevated temperature degradation can be a futile exercise.

Fortunately, the components of interest in this program will be exposed to a relatively constant environment, high vacuum and low temperature. In such a situation, predicted aging rates are much more likely to be valid.

RESULTS AND DISCUSSION

Elastomers and Plastics

Various investigators have determined that the effect of vacuum on polymers is not one of evaporation or sublimation, but a breakdown of the polymer chain to smaller, more volatile fragments. The molecular weight of these fragments is not well established and neither is the equilibrium decomposition pressure. It is therefore necessary to turn to direct experimental studies of the weight loss of polymers in vacuum.

A second, and likely more serious, mode by which properties of elastomers can be altered is through removal by evaporation of additives or impurities introduced during synthesis or formulation of the resin. In some cases, the polymer is degraded by vaporization of components essential to the optimum properties of the part. In others, properties can be improved by the same mechanism wherein impurities are outgassed. One general danger of the volatilization process lies in the contamination of electrical contacts and other surfaces that depend upon an uncontaminated surface in order to function properly. This volatilization phenomenon is ever-present because in space there is no back pressure to impede the evaporation of volatile constituents.

Polytetrafluoroethylene. - Because of commercial importance, the degradation of polytetrafluoroethylene has been widely investigated and discussed[3-9]. A summary of kinetic data by various workers is given in Table III.

There has been a minor controversy in the literature[10] concerning the possibility of a change in reaction order and activation

TABLE III

SUMMARY OF KINETIC DATA FOR POLYTETRAFLUOROETHYLENE

Method	Temperature °C	Reaction Order	Activation Energy kcal/mole	Arrhenius Factor, sec^{-1}	Reference
Isothermal Weight Loss	480-510	First	80.5	4.7×10^{18}	3
Isothermal Weight Loss	360-510	First	83	3×10^{19}	4
Thermogravimetric Analysis	450-550	First	75 ± 4		5
Thermogravimetric Analysis	470-530	First	72 ± 3		6
Isothermal Weight Loss	480-510	First	76	10^{19}	7
Isothermal Pressure Measurements	480-580	First	78	6×10^{19}	8
Isothermal Pressure Measurements	Up to 600	First	74	2.8×10^{18}	9

energy as the reaction proceeds. This controversy does not, however, alter the general conclusions that the reaction in an inert atmosphere proceeds with a high activation energy and an Arrhenius factor of approximately 10^{19} sec^{-1}.

Using a conservative value of 70 kcal/mole as the activation energy, one calculates from the Arrhenius equation that the rate of weight loss at 25°C is lower than the rate at 350°C by a factor of 10^{30}. The rate of weight loss at 350°C is reported to be 2×10^{-6} %/min. The predicted value at 25°C is, therefore, approximately 10^{-36} %/min, producing a total weight loss over an 8-year mission of only 10^{-29} to 10^{-30}%. If the predicted value is off by as much as many orders of magnitude, it is obvious that the total amount of degradation is still insignificant.

These predictions are supported by the work of Bringer[(11)] who determined the extent of outgassing of Teflon* at 25°C. The outgassing rate is 1.6×10^{-7} torr-liters/sec-cm^2 which is less than the value of 3.7×10^{-7} torr-liters/sec-cm^2 for aluminum. Analyses of gases evolved from vacuum outgassing of Teflon have indicated that no degradation occurs in high-vacuum service. The identity of the gases evolved at low temperatures is shown in Table IV and indicates that the effect of vacuum on Teflon at low temperatures is to remove adsorbed gases.

Viton. - The co-polymer of vinylidene fluoride and hexafluoropropylene is one of the most stable elastomers available at the present time. Various formulations are available consisting of different proportions of the two comonomers and different molecular weights. Kinetic data have

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*Registered trademark of E. I. DuPont deNemours and Company, Inc.

TABLE IV

GASES EVOLVED FROM TEFLON EXPOSED TO VACUUM

Temperature	Gas Composition (%)			
°C	H_2O	CO_2	N_2	O_2
71	12		65	25
180	14		64	21
200	6	2	72	19

been obtained for the degradation in vacuum for several formulations and are shown in Table V[13-15]. Differences in behavior are noted; however, all activation energies are 45 kcal/mole or greater and the most rapid rate of reaction observed was only 0.18%/min at 350°C. Again using the Arrhenius equation as a basis for extrapolation and assuming worst-case conditions (i.e., a polymer with a weight loss rate at 350°C of 0.18%/min with an activation energy of 45 kcal/mole), a rate of weight loss at 25°C of <u>ca.</u> 10^{-18}%/min can be calculated. This rate would result in a total weight loss after 8 years in deep space of only 10^{-12}%. Even allowing for considerable error in these calculations, it is obvious that no significant deterioration will occur.

Frequently, compounders of elastomeric materials will add ingredients to the resin systems to improve properties. The widespread use of plasticizers as additives to improve flow properties of elastomers used as seals is a typical example. The removal of such additives by evaporation in high vacuum is likely to contribute more to alterations in properties during transit than chemical degradation. Unfortunately, property changes caused by evaporation of additives are difficult, if not impossible, to

TABLE V

KINETIC DATA FOR THERMAL DEGRADATION OF VINYLIDENE FLUORIDE COPOLYMERS IN VACUUM

Copolymer Units	Activation Energy kcal/mole	Rate of Weight Loss at 350°C %/min	Reference
CF_2CH_2/CF_3CFCF_2	57	0.04	13
70%/30%	46	0.04	14
CF_2CH_2/CF_3CFCF_2 70%/30% (Higher molecular weight than above)	48	0.05	14
CF_2CH_2/CF_3CFCF_2 60%/40%	45	0.05	14
CF_2CH_2/CF_2CFCl	61	0.06	13
67%/33%	54	0.06	14
CF_2CH_2/CF_2CFCl	61	0.06	13
53%/47%	50	0.12	14
CF_2CH_2/CF_2CFCl 19%/81%	68	0.18	14
CF_2CH_2/CF_2CFCl Composition unknown	53	----	15

accurately predict because many types of additives are used commercially and formulations may vary from one compounder to another.

Silicone elastomers. - The effect of exposure to vacuum on various silicone rubbers has been determined by several investigators[16-20]. Fulk and Horr[16], for example, have determined stationary state weight loss and weight loss to stationary state for Dow RTV-521, RTV-503, RTV-501, RTV-5313-5314 and G.E. elastomers RTV-40, RTV-60, RTV-11 and LTV-602. Data are shown in Table VI.

TABLE VI

WEIGHT LOSS OF SILICONE ELASTOMERS IN VACUUM AT 50°C

Material	Total Weight Loss to Stationary State (gm/cm^2)	Time to Stationary State (hr)	Rate at Stationary State ($gm/cm^2\ hr$)
Dow RTV 521	4.5×10^{-3}	68	10^{-5}
Dow RTV 503	4.2×10^{-3}	68	2×10^{-5}
GE RTV 40	5×10^{-3}	68	2.7×10^{-5}
GE RTV 60	5.3×10^{-3}	68	2.8×10^{-5}
Dow RTV 501	5.8×10^{-3}	58	3.7×10^{-5}
GE RTV 11	4.1×10^{-3}	44	3.7×10^{-5}
GE LTV 602 (potting compound)	1.2×10^{-2}	44	10^{-4}
Dow RTV 5313-5314 (potting compound)	4.3×10^{-2}	68	3.8×10^{-4}

If the stationary state values for weight loss would continue throughout a mission of 8 years' duration, total weight losses of up to 1 gm/cm^2 would be predicted which would lead to significant changes in properties.

Bundy[17], however, has reported data, from his studies of weight loss of silicone rubbers exposed to vacuum and elevated temperature, that the total weight loss from a variety of silicones is between 1 and 2% (Table VII).

TABLE VII

PERCENT WEIGHT LOSS FOR SILICONE RUBBER UNDER VACUUM-THERMAL CONDITIONS[17]

Silicone Rubber and Manufacturer	Weight Loss, Percent at 300°F			
	Time, days			
	1	4	7	10
RTV 891, Dow Corning Corp.	1.49	1.73	1.80	-
Silicone, Lord Mfg. Co.	0.70	0.93	1.02	1.02
RTV-60, General Electric Co.	1.05	1.30	1.36	-
PR-1930-1/2, Products Research				
Ambient temperature cure	1.64	1.86	1.96	-
Post cured 6 hrs, 300°F	0.77	1.00	1.12	-
Silicone Rubber, Nylon Reinforced Irvington Division, MMM Co.	1.48	1.71	1.78	-

Pressure 10^{-6}

These results suggest that exposure of silicone rubbers to high vacuum results in an immediate weight loss followed by a stationary state rate of approximately 10^{-5} gm/cm^2-hr which continues to a total loss of 1% to 2%.

This behavior is indicative of evaporation of low molecular weight impurities introduced during synthesis or formulation. A reasonable

prediction is, therefore, that silicone elastomers would perform properly throughout a deep space mission.

Polymides (Vespel-1 SP-1). - Vespel SP-1 is the base resin of a polymide plastic produced by DuPont. Polymide resins have been shown by many investigators to possess excellent long-term stability[21]. The useful life in vacuum continuously exposed to temperatures greater than 200°C has been estimated to be longer than 10 years. Polymide parts also give very low outgassing at elevated temperatures in vacuum. For example, at 500°F, the rate of weight loss in vacuum for Vespel SP-1 is less than 10^{-10} gm/cm^2-sec.

Thermal Control

Thermal control of the space probe during transit is maintained by the balance between heat generated by radioisotope heaters and radiative/conductive losses through the probe and the multi-layer insulation blanket. Radioisotope heaters are a reliable and proven source of energy. Proper thermal control, therefore, will largely depend upon the behavior after aging of the polyurethane and carbon phenolic insulation and the multi-layer insulation blanket.

Phenolic and polyurethane insulation. - Thermoset plastics, such as phenolics or polyurethane foam, may suffer weight losses upon exposure to high vacuum. However, it has been reported that the weight losses generally do not result in significant changes in properties[22].

Podlaseck and Suhorsky have explored the relation between weight loss under vacuum and physical properties of phenolic resins[23]. They report that a correlation of weight loss and mechanical properties may not

be valid since most of the weight loss in phenolic polymers is due to the release of water formed during the condensation reaction or water generated due to postcuring at elevated temperatures. In the latter case, weight loss would be indicative of further crosslinking leading to higher strength.

Polyurethane foams have also been demonstrated to be largely unaffected by exposure to vacuum. As with phenolics, weight losses of polyurethanes can be significant. Evidence suggests[19, 20], however, that even at temperatures where true degradation occurs, it is limited to surface depolymerization followed by sublimation of the linear molecular weight fragments. The polymer below the surface retains its identity and properties.

Multi-layer insulation blanket. - The use of metallized plastic film as a thermal control surface has received considerable attention based on favorable absorbance/emittance ratio, high transparency and a stable solar absorbance. The majority of the work reported in the literature is confined to films containing Teflon as the transparent plastic and intended for use in systems in which the film was bonded directly to a radiator panel. The time periods of interest in literature studies were generally from one to three years, typical of earth orbit missions.

Under these conditions three areas of potential problems have been reported[24-26]: (1) delamination of the metallized layer from the Teflon film; (2) bond failure between the film and radiator; and (3) radiation (UV) damage of the plastic portion of the metallized film. Fortunately, none of these problems should be present in the multi-layered insulation

blanket. Mylar or Kaplan are currently being projected to be used as the plastic portion of the film. Both provide a superior surface for bonding than does the relatively inert Teflon surface. The use of a blanket rather than bonding the film directly to a radiator eliminates the potential problem of bond delamination. Finally, the limited exposure to sunlight during transit should cause no damage to systems which have been demonstrated to withstand up to 800 equivalent sun hours.

One problem with MLI's which has come to light is arc-over[27]. This occurs as the result of electrical charge build-up in the presence of high radiation fields. When a sufficient potential is developed, electrical discharge or arc-over occurs. This perforates the plastic film and vaporizes the metallized coating in the area. Accumulation of charges on the metallized film can be prevented by grounding the metal foil. However, this does not prevent build-up of charge and arc-over in the insulating polymer film.

Electronic Components and Devices

As an addition to the program, a survey was conducted to find information on the long-life reliability of electronic components and devices. This field is so broad that it could constitute a study program in itself. Therefore, the information presented represents a general overview. Conclusions regarding general classes may not apply to specific items within that class and failures of specific devices may not apply to the same devices manufactured by another vendor.

Various schemes have been devised to evaluate the reliability of electronic components and equipment. The principal states of activation used are storage (zero activation level), dormancy (10% or less of normal activation), power on-off cycling (from zero activation level to normal activation level and back to zero again, or vice versa), and energized (normal activation level). Only a limited amount of information is available on components tested using the second and third states of activation. Furthermore, much of the information on stored devices (e.g., RADC-TR-67-308, items from 8 to 15 years old) can be considered obsolete as a result of state-of-the-art advances in microelectronic and semiconductor devices. For this reason, all information on vacuum tubes and vacuum tube circuits was omitted.

In 1970, Martin Marietta Corporation, Denver Division compiled a "Handbook of Long-Life Space Vehicle Investigations"[28]. They found that solar cells, memory core devices, solenoid valves, ordnance valves, and transducers (depending upon type and application) all have sufficiently high reliabilities that life expectancies of up to 10 years in the space environment can be expected. However, high radiation levels may reduce the life expectancy of the first two components.

In addition, the reliability of light-sensitive devices, particularly of photo-multiplier tubes, is severely affected by excessive heat, excessive light, and excessive high-energy radiation.

In the case of motor-driven switches, the life-limiting factor appears to be contamination of the switch contacts. This contact problem also applies to relays. Diamond[29] found that 85% of relay failures displayed contact defects.

Schwartz and Soltis[30], in a study of silver oxide batteries for synchronous orbit and planetary missions, found that the predominant problem area was failure of glued seams on the negative plate separator bag. Design improvements were made, but data on their performance were not available.

A study of nickel-cadmium batteries by McCallum and Miller[31] reveals that degradation of cell quality accelerates 10-fold for each 30°C of temperature difference between inside and outside of the battery. Additionally, at 25°C a 10-fold increase in discharge rate yielded 30-fold increase in the rate of cell quality degradation. At 40°C the same increase in discharge rate yielded a 100-fold increase in degradation rate.

For microcircuits, problems have been noted with voltage drift, loss of gain, and latch-up[32-33]. These can be caused by incipient defects on the chip which lead to:

(1) Inversion of a lightly doped semiconductor material,

(2) Electromigration,

(3) Leakage current,

(4) Channeling,

(5) Dielectric breakdown,

(6) Etching of aluminum metallization,

(7) Opening of aluminum interconnection,

(8) Aluminum spiking across P-N junction as result of static discharge,

(9) Ionic contamination, and

(10) Deleterious intermetallic compounds.

Dean and Harper[34] found that electronic screening tests could be used to predict the majority of failures occurring as a result of step-stress testing of digital-type microcircuits. Burn-in screening can be used to improve the reliability of integrated circuits used[35]. In this same study, Brown surveyed manufacturers and users of integrated circuits and compiled failure mode data (such as shown in Fig. 2) for various package types of devices.

Storage reliability tests have been in progress for up to 5 years for some 500 electronic items at Martin Marietta Corporation, Orlando Division under a contract for the U.S. Army Missile Command. The test items include resistors, capacitors, diodes, transistors, integrated circuits, etc. of various types. To date, no failures have been observed in the retesting program. However, it must be noted that all of these items are "high" reliability grade components.

Dormancy and power on-off-cycling effects on electronic equipment and part reliability have been studied[36]. Results indicate no significant difference between the failure rates for dormant and storage modes of testing. Power on-off cycling, on the other hand, does have a definite adverse effect upon electronic equipment reliability. The degree to which reliability is affected depends upon several factors such as part quality, cyclic rate, temperature effects, environment and transient suppression capabilities of the system. Analysis of the failure mode indicates an overwhelming tendency of power on-off cycling to induce failures in the open mode. Approximately 90% of the analyzed failures were opens. This is attributed to expansion and contraction effects which take place when devices are energized and

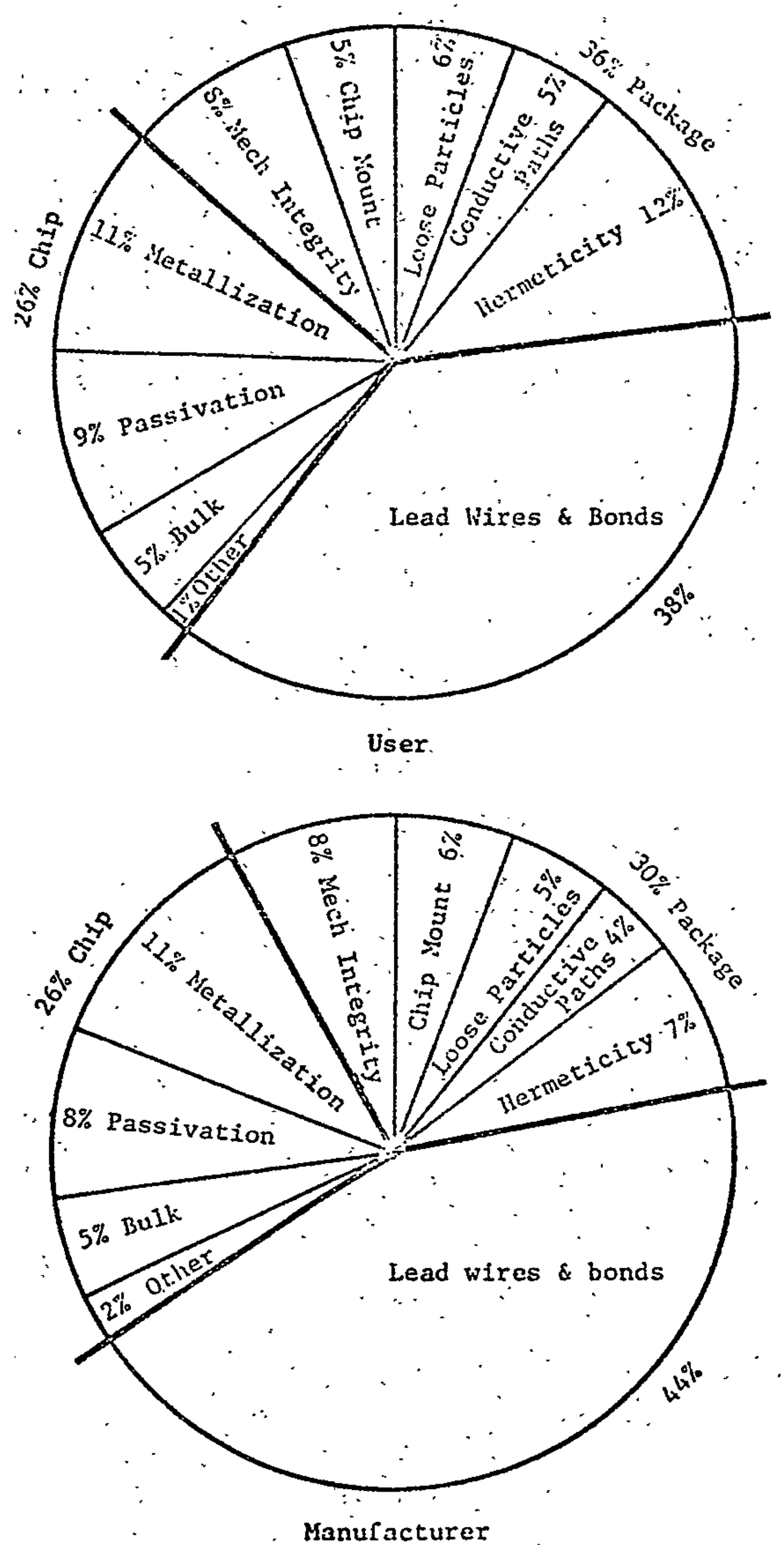

Fig. 2. Ceramic Dual-In-Line Failure Predominance

de-energized. Power on-off cycling can be particularly effective in precipitating failure of incipient defects -- such as cracks, poor solder joints or welds, etc. -- the reason being that power cycling can induce a localized hot spot at the area where the defect exists.

Results of the dormancy and power on-off cycling effects on part reliability are given in Tables VIII-XI. These results are listed by part type, part hours (or part cycles), number of failures, and failure rate per billion hours.

All of the information found on electronic component reliability is for earth atmosphere exposure. Exposure to the vacuum of space would be expected to contribute to the failure of components where leakage (e. g., batteries and wet electrolytic capacitors) and migration of contaminants (e. g., to electrical contacts or in microcircuits) would be possible.

From the information surveyed, it became apparent that the reliability of electronic components is dependent upon several factors, such as part quality, usage, temperature effects, environment, transient suppression capabilities. Furthermore, in order to insure maximum reliability, it is necessary to carry out an extensive and exhaustive test and screening program, including burn-in screening and power on-off cycling.

Pyrotechnic Devices

The initiation of certain sequential events is dependent upon the proper functioning of pyrotechnic devices. It is, therefore, necessary to determine whether long-term, deep space missions will have a deleterious effect on these devices.

TABLE VIII[36]

OBSERVED DORMANCY FAILURE DATA, MILITARY STANDARD PARTS

Part Type	t_D Part-Hours ($\times 10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Antennas and Peripheral Equip.	4.260	0	<234.74
Antennas	0.610	0	<1639.34
Attenuators	0.610	0	<1639.34
Circulators, Four Port	1.010	0	<990.10
Couplers, Antenna	1.220	0	<819.67
Couplers, Directional	0.810	0	<1234.57
Capacitors	10876.852	18	1.65
General Class	9406.075	11	1.17
Ceramic	729.386	3	4.11
Chip	18.301	0	<54.64
Glass	4.554	0	<219.59
Metalized Paper	329.000	2	6.08
Mica	296.573	0	<3.37
Mylar	0.109	0	<9174.31
Tantalum, Foil	7.698	0	<129.90
Tantalum, Slug, Wet	0.843	2	2372.48
Variable, Trimmer, Piston	84.313	0	<11.86
Filters	26.586	1	37.61
Ceramic, Bandpass	0.126	0	<7936.51
Ceramic, Feed-Through	0.378	1	2645.50
Transmittal	0.378	0	<2645.50
RC, Low Pass	25.704	0	<38.90
Flight Instruments, Missile	264.000	25	94.70
Fuses	1.500	0	<666.67

TABLE VIII
(continued)

Part Type	t_D Part-Hours ($x10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Inductive Devices	6.174	0	<161.97
Chokes	0.756	0	<1322.75
Coils, RF	5.418	0	<184.57
Inertial Guidance Devices	1.008	0	<992.06
Accelerometers	0.378	0	<2645.50
Angular	0.252	0	<3968.25
Linear	0.126	0	<7936.51
Gyros, Rate	0.630	0	<1587.30
Microwave Devices, Isolator	0.126	0	<7936.00
Relays	472.000	18	38.14
Resistors	31992.482	17	0.53
General Class	23097.618	11	0.48
Carbon Composition	4652.000	0	<0.21
Carbon Film	6.134	0	<163.03
Metal Film	3290.034	0	<0.30
Thermistor	95.284	3	31.48
Wirewound	840.846	2	2.38
General Class	135.547	0	<7.38
Power	376.299	2	5.31
Precision	329.000	0	<3.04
Variable	10.566	1	94.64
Semiconductors	10351.900	65	6.28
Diodes	6871.000	41	5.97
General Class	6036.000	41	6.79
Low Power	228.000	0	<4.39
Zener	607.000	0	<1.65
Integrated Circuits, Class C	1952.900	8	4.10
Digital	1952.900	8	4.10
Transistors, Silicon	1528.000	16	10.47
Surge Arrestors, Sparkgap	7.290	0	<137.17
Transformers	509.000	9	17.68
Tubes	1.017	14	13765.98
Valves, Hydraulic, Servo	0.756	0	<1322.75
Total	54,514.951	167	3.06

TABLE IX [36]

OBSERVED DORMANCY FAILURE DATA, HIGH RELIABILITY PARTS

Part Type	t_D Part-Hours $(x10^6)$	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Batteries, Silver-Zinc	0.200	0	<5000.00
Capacitors	13295.384	15	1.13
General Class	4165.800	2	0.48
Aluminum Electrolytic	6.080	0	<164.47
Ceramic	3103.041	2	0.64
Feed Through	11.551	0	<86.57
Glass	294.843	0	<3.39
Metallic Film	2.200	0	<454.55
Mica	354.207	1	2.82
Mica, Dipped	8.820	0	<113.38
Mica, Reconstituted	0.410	0	<2439.02
Paper	18.645	0	<53.63
Plastic	30.222	1	33.09
Polycarbon Film	23.728	1	42.14
Polystyrene	9.500	0	<105.26
Tantalum, Gen Class	2612.092	2	0.77
Tantalum, Foil	144.782	0	<6.91
Tantalum, Solid	2029.836	1	0.49
Tantalum, Wet	430.093	4	9.30
Teflon	0.376	0	<2659.57
Variable, Air	40.630	1	24.61
Variable, Ceramic	0.322	0	<3105.59
Variable, Glass	8.206	0	<121.86
Connective Devices	91158.575	1	0.01
Connectors	800.975	1	1.25
Pins	55437.600	0	<0.02
Soldered Connections	34920.000	0	<0.03
Crystals	20.065	0	<49.84
Electromechanical Devices	23.720	0	<42.16
Counters	1.400	0	<714.29
Fans	1.020	0	<980.39
Axial	0.610	0	<1639.34
Centrifugal	0.410	0	<2439.02
Motors	6.600	0	<151.52
Blower	1.500	0	<666.70

TABLE IX
(continued)

Part Type	t_D Part-Hours (x10^6)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
DC	0.200	0	<5000.00
Servo	1.900	0	<526.32
Torque	3.000	0	<333.33
Resolvers	8.800	0	<113.64
Slip Rings	5.900	0	<169.49
Filters	98.532	0	<10.15
General Class	88.488	0	<11.30
EMI	10.044	0	<99.56
Fuses	1.500	0	<666.67
Heaters	1.900	0	<526.32
Inductive Devices	655.527	0	<1.53
Chokes	9.437	0	<105.97
Coils	364.981	0	<2.74
General Class	79.181	0	<12.63
Radio Frequency	285.800	0	<3.50
Delay Lines	0.752	0	<1329.79
Inductors	261.557	0	<3.82
Reactors	18.800	0	<53.19
Inertial Guidance Devices	5.220	8	1532.57
Accelerometers	2.610	6	2298.85
General Class	0.410	0	<2439.02
Pulsed Integrating Pendulum	2.200	6	2727.27
Gyros	2.610	2	766.28
General Class	0.410	0	<2439.02
Inertial Reference, Integrating	2.200	2	909.09
Lamps	37.500	2	53.33
Annunciator	0.700	0	<1428.27
Electroluminescent	27.300	1	36.63
Incandescent	9.500	1	105.26
Oscillator / Isolator	0.200	0	<5000.00
Magnetic Cores	24771.000	0	<0.04
Relays	567.905	10	17.61

TABLE IX
(continued)

Part Type	t_D Part-Hours (x10^6)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Resistors	32518.917	2	0.06
General Class	4757.200	0	<0.21
Carbon Composition	6896.740	0	<0.14
Carbon Film	107.934	0	<9.26
Metal Film	12533.498	1	0.08
Thermal	1.925	0	<519.48
Thermistor	4.578	0	<218.44
Tin Oxide	4655.400	0	<0.21
Wirewound	3499.183	0	<0.29
General	601.582	0	<1.67
Power	2108.571	0	<0.47
Precision	788.020	0	<1.27
Heater Element	1.010	0	<990.10
Variable	62.459	1	16.01
General Class	36.898	0	<27.10
Film	23.300	1	42.92
Plastic	0.756	0	<1322.75
Wirewound	1.505	0	<664.45
Semiconductors	38573.832	33	0.86
Diodes	18761.312	7	0.37
General Class	9415.329	3	0.32
Low Power	7605.035	3	0.39
Medium Power	694.435	0	<1.44
High Power	133.321	0	<7.50
Micro	11.364	0	<88.00
Tunnel	1.912	0	<523.01
Varactor	1.913	0	<522.74
Zener	898.003	1	1.11
Integrated Circuits	9027.236	14	1.55
Class A	5863.736	6	1.02
Digital	5328.202	5	0.94
Linear	535.534	1	1.87
Class B	3120.254	7	2.24
General Class	615.000	0	<1.63
Digital	2269.720	5	2.20
Linear	235.534	2	8.49
Hybrid Class B (thin film)	43.246	1	23.12
Silicon Controlled Rectifiers	57.606	0	<17.36

TABLE IX
(continued)

Part Type	t_D Part-Hours ($x10^6$)	F_D Fail-ures	λ_D Failure Rate (Per Billion Hours)
Transistors,			
Silicon	10662.041	12	1.13
General Class	3146.791	3	0.95
Low Power	5482.804	6	1.09
General Category	1761.401	1	0.57
NPN	3035.643	4	1.32
PNP	685.760	1	1.46
Medium Power	523.933	0	<1.91
General Class	86.000	0	<11.63
NPN	249.326	0	<4.01
PNP	188.607	0	<5.30
High Power	1435.810	3	2.09
General Class	192.663	1	5.19
NPN	791.156	2	2.53
PNP	451.991	0	<2.21
Field Effect	71.674	0	<13.95
Unijunction	1.027	0	<973.71
Transistors, Germanium	65.637	0	<15.24
Low Power, NPN	20.834	0	<48.00
Low Power, PNP	44.803	0	<22.32
Solar Cells	748.583	8	10.69
Switches	50.951	2	39.25
General Class	32.100	0	<31.15
Electronic	1.220	0	<819.67
Humidity Control	0.410	0	<2439.02
Indicator Light	1.220	0	<819.67
Inertial	0.410	0	<2439.02
Micro	4.226	0	<236.63
Pressure	0.610	0	<1639.34
RF	0.956	0	<1046.03
RF, Ferrite	0.139	0	<7194.24
Stepping	5.000	2	400.00
Thermostatic	3.650	0	<273.97
Toggle	1.010	0	<990.10
Temperature Sensors	0.200	0	<5000.00
Thermostats	3.724	0	<268.53
Transformers	2928.309	3	1.02
General Class	1987.016	1	0.50

TABLE IX
(continued)

Part Type	t_D Part-Hours ($x10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Audio Frequency	632.810	2	3.16
High Voltage	6.651	0	<150.34
Low Voltage	1.319	0	<758.15
Power	83.028	0	<12.04
Pulse	9.514	0	<105.11
Radio Frequency	207.771	0	<4.81
Saturable	0.200	0	<5000.00
Tubes, Sprytron	0.410	0	<2439.02
Video Signal Detectors	0.610	0	<1639.34
Total	205,462.764	84	0.41

TABLE X[36]

OBSERVED POWER ON-OFF CYCLING DATA, MILITARY STANDARD PARTS

Part Type	C Part-Cycles x 10^6	F_C Failure	λ_C Failure Rate (per billion part-cycles)
Antennas and Peripheral Equipment	0.171	0	<5848
Antennas	0.013	0	<76923
Attenuators	0.026	0	<38462
Circulators, 4 Port	0.044	0	<22727
Couplers, Antenna	0.053	0	<18868
Couplers, Directional	0.035	0	<28571
Capacitors	6.758	0	<148
General Class	0.534	0	<1873
Ceramic	0.640	0	<1563
Glass	3.152	0	< 317
Mica	0.065	0	<15625
Paper	0.320	0	<3125
Plastic	0.272	0	<3676
Tantalum, Foil	0.288	0	<3472
Tantalum, Solid	1.120	0	<893
Tantalum, Wet	0.368	0	<2717
Choppers	0.016	0	<62500
Filters	0.011	0	<90909
Fuses	0.104	0	<9615
Relays	0.923	0	<1083
Resistors	48.231	0	<21
Carbon Composition	14.384	0	<70
Metal Film	32.135	0	<31
Wirewound	0.960	0	<1042
Variable	0.752	0	<1330
Semiconductors	118.156	242	2048
Diodes	24.382	0	<41
Low Power	22.818	0	<44
High Power	0.112	0	<8929
Zener	1.452	0	<689
Transistors	93.774	242	2581
Low Power	92.794	241	2597
NPN	82.320	241	2928
PNP	10.474	0	<95
Medium Power	0.304	0	<3289
NPN	0.048	0	<20833
PNP	0.256	0	<3906
High Power	0.676	1	1479
NPN	0.404	1	2475
PNP	0.272	0	<3676
Surge Arrestors, Spark Gap	0.322	0	<3106
Switches	1.200	0	<833
Transformers	0.837	0	<1195
TOTAL	176.729	242	1369

TABLE XI(36)

OBSERVED POWER ON-OFF CYCLING DATA, HIGH RELIABILITY PARTS

Part Type	C Part-Cycles x 10^6	F_C Failures	λ_C Failure Rate (per billion part-cycles)
Capacitor	20101.477	2	0.10
Aluminum	0.269	0	<3717.47
Ceramic	9539.056	0	<0.10
Glass	277.905	0	<3.60
Metal Film	0.012	0	<83333.33
Mica	0.720	0	<1388.89
Mica, Reconstituted	0.017	0	<58823.53
Mylar	0.705	1	1418.44
Paper	0.044	0	<22727.27
Plastic/Paper	0.012	0	<83333.33
Polystyrene	0.096	0	<10416.67
Tantalum, General Class	10273.777	0	<0.10
Tantalum, Foil	0.053	0	<18867.92
Tantalum, Solid	8.742	1	114.39
Tantalum, Wet	0.012	0	<83333.33
Variable	0.057	0	<17543.86
Connective Devices	9493.722	0	<0.11
Connectors	9075.331	0	<0.11
Connector Pins	418.391	0	<2.39
Crystals	0.035	0	<28571.43
Electromechanical Devices	0.195	1	5128.21
Counters	0.012	0	<83333.33
Fans, Axial	0.026	0	<38461.54
Fans, Centrifugal	0.017	0	<58823.53
Motors	0.044	1	22727.27
Blower	0.008	0	<125000.00
DC	0.004	0	<250000.00
Servo	0.016	1	62500.00
Torque	0.016	0	<62500.00
Resolvers	0.063	0	<15873.02
Slip Rings	0.033	0	<30303.03
Filters	0.004	0	<250000.00
Heaters	0.012	0	<8333.33
Illuminating Devices	11.128	23	2066.86
Lamps	2.863	21	7334.96
General Class	2.608	20	7668.71
Annunciator	0.008	0	<125000.00
Electroluminescent	0.155	0	<6451.61
Incandescent	0.092	1	10869.57
Light Emitting Diode	8.265	2	241.98

TABLE XI
(continued)

Part Type	C Part-Cycles x 10^6	F_C Failures	λ_C Failure Rate (per billion part-cycles)
Inductive Devices	553.830	0	<1.81
Chokes	0.016	0	<62500.00
Coils	499.090	0	<2.00
General Class	498.200	0	<2.01
Radio Frequency	0.890	0	<1123.60
Delay Lines	54.304	0	<18.41
Inductors	0.248	0	<4032.26
Reactors	0.172	0	<5813.95
Inertial Guidance Devices	0.016	0	<62500.00
Accelerometer	0.008	0	<125000.00
Gyros	0.008	0	<125000.00
Magnetic Cores	150.528	0	<6.64
Oscillators, Isolator	0.004	0	<250000.00
Relays	0.798	0	<1253.13
Resistors	36119.508	1	0.03
General Class	1.733	0	<577.03
Carbon Composition	122.312	0	<8.18
Carbon Film	0.185	0	<5405.41
Metal Film	32309.048	0	<0.03
Thermistor	0.033	1	30303.03
Thermal Resistor	16.380	0	<61.05
Tin Oxide	39.110	0	<25.57
Wirewound, General Class	3590.500	0	<0.28
Wirewound, Power	11.502	0	<86.94
Wirewound, Precision	0.040	0	<25000.00
Wirewound, Heater Element	0.040	0	<25000.00
Variable, General Class	0.394	0	<2538.07
Variable, Metal Film	1.031	0	<969.93
Variable, Wirewound	27.200	0	<36.76
Semiconductors	51066.492	5	0.10
Diodes	13226.508	0	<0.08
General Class	0.022	0	<45454.54
Low Power	10928.512	0	<0.09
Medium Power	0.483	0	<2070.39
High Power	463.399	0	<2.16
Tunnel	0.331	0	<3021.15
Zener	1833.761	0	<0.55
Integrated Circuits	29721.597	0	<0.03
Digital	28267.103	0	<0.04
Class A	22.717	0	<44.02
Class B	28244.386	0	<0.04

TABLE XI
(continued)

Part Type	C Part-Cycles x 10^6	F_C Failures	λ_C Failure Rate (per billion part-cycles)
Linear	1454.494	0	<0.69
Class A	0.134	0	<7462.69
Class B	1454.360	0	<0.69
Transistors, Silicon	8118.387	5	0.62
General Class	0.008	0	<125000.00
Low Power	7523.568	0	<0.13
NPN	4571.260	0	<0.22
PNP	2952.308	0	<0.34
Medium Power	3.936	0	<254.07
NPN	2.907	0	<344.00
PNP	1.029	0	<971.82
High Power	589.444	5	8.48
NPN	507.841	5	9.85
PNP	81.603	0	<12.25
Field Effect	1.085	0	<921.66
SCR	0.342	0	<2923.98
NPNP	0.161	0	<6211.18
PNPN	0.181	0	<5524.86
Unijunction	0.004	0	<250000.00
Switches	0.550	4	7272.72
General Class	0.201	4	19900.50
Electronic	0.053	0	<18867.92
Indicator Light	0.053	0	<18867.92
Inertial	0.008	0	<125000.00
Humidity Control	0.017	0	<58823.53
Pressure	0.013	0	<76923.08
Thermostatic	0.161	0	<62111.80
Toggle	0.044	0	<22727.27
Temperature Sensors	0.004	0	<250000.00
Thermostats	0.021	0	<47619.05
Transformers	138.618	9	64.93
General Class	138.201	9	65.12
Audio Frequency	0.017	0	<58823.53
Power	0.111	0	<9009.01
Pulse	0.066	0	<15151.52
Radio Frequency	0.215	0	<46511.63
Saturable	0.008	0	<125000.00
Tubes, Sprytron	0.017	0	<58823.53
Video Signal Detectors	0.026	0	<38461.54
TOTAL	117636.985	45	0.38

For this program the single bridgewire Apollo standard initiation (SBASI), containing a pyrotechnic mixture of zirconium-potassium perchlorate ($Zr/KClO_4$), was selected as a representative device for testing long-life reliability. The SBASI (shown in Fig. 3) is a 1-amp, 1-watt, no-fire single bridgewire cartridge, with a 1-ohm bridgewire. All-fire current is 3.5 amps; however, the recommended firing current is 5 amps, to provide a safety factor.

Prior work[37] has shown the ingredients ($Zr/KClO_4$) to be capable of withstanding up to 10 years in a space environment at 66°C without exhibiting significant change. However, the functional performance of the mixture was not measured as a part of the study and the mixture was not installed in an actual device where possible interaction with the other materials of construction could affect performance.

During that study, the mixture was found to have a decomposition rate constant of 1.2×10^{-12}/sec at 66°C with an activation energy of 30 kcal/mole in a closed-volume vacuum system. Using these data and the method presented in the report, the accelerated aging temperature was calculated such that one month of accelerated aging equals two years of real-time aging at 66°C. This permits the simulation of 8 years of aging in a period of only 4 months.

For this program, six SBASI devices were aged in a vacuum oven at $92^{\circ} \pm 2^{\circ}$C for a period of 4 months. These devices plus six unaged devices, as controls, were functionally tested to determine if their performance was significantly affected by exposure to the equivalent of 8 years in a space environment.

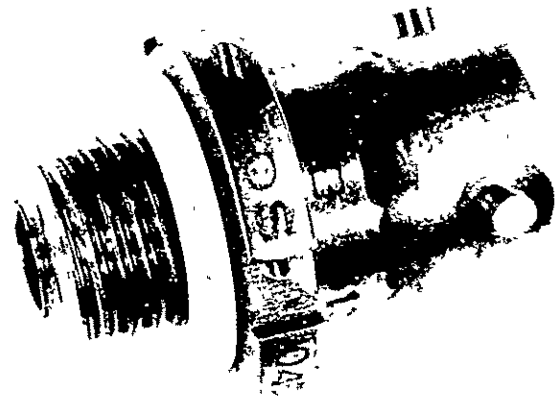

Fig. 3. Single Bridgewire Apollo Standard Initiation

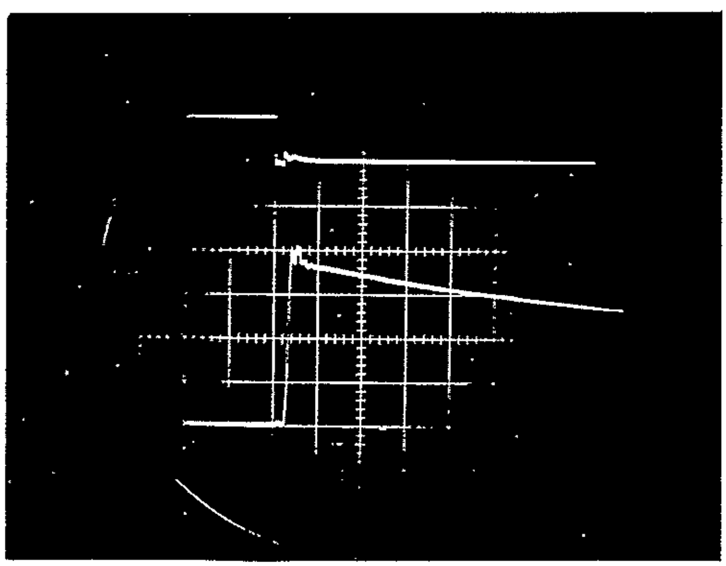

Fig. 4. Bridgewire Current and Pressure Traces for SBASI S/N 489

The parameters measured during the functional testing were: bridgewire burn-out time, ignition delay, peak pressure, and time to peak pressure. Each device was initiated using a 5-amp firing current supplied by a constant current source. The devices were fired into a 10-cc closed volume cell, with the pressure sensed by a quartz pressure transducer mounted perpendicular to the axis of the cell and SBASI. Test parameters were displayed on an oscilloscope and photographed, as shown in Fig. 4.

Results obtained for the functional testing of the SBASI are shown in Table XII. In addition to the data shown in the Table, the insulation resistance, case to pins resistance, was measured for each device prior to testing. This value was greater than 12 Meg Ω in all cases.

Essentially, all of the devices had identical bridgewire burn-out times, ignition delays, and times to peak pressure. One of the aged devices (S/4 491) apparently misfired. The peak pressure for this unit was only 40% of the average of the other aged values and it took 0.1 msec longer to reach that value. Otherwise, no significant differences are observed between the controls and the aged devices. The average of the peak pressure values for the controls is 773 psi; for the aged devices (excluding S/N 491) it is 783 psi. Spread of peak pressure values is slightly greater for the aged devices (excluding S/N 491) than the controls, 95 psi versus 60 psi. Considering the similarity between the functional performance of the control and aged devices, failure of S/N 491 device to fire properly is believed to be a random misfire rather than the result of aging of the SBASI.

As a result, we conclude that aging does not significantly affect the functional performance of the SBASI devices and that they should be capable of withstanding up to 8 years' exposure to the space environment.

TABLE XII

SBASI TEST RESULTS

Device S/N	Bridgewire Resistance	Peak Press., Pk.	Time To Pk.	Ignition Delay	Bridgewire Burn-Out
Controls	Ω	psi	msec	msec	msec
471	1.04	770	1.2	1.1	1.0
476	1.02	790	1.2	1.1	1.0
478	1.02	775	1.2	1.1	1.0
480	1.03	740	1.2	1.1	1.0
484	1.02	760	1.2	1.1	1.0
489	1.04	800	1.2	1.1	1.0
Aged					
470	1.01	820	1.2	1.1	1.0
473	1.02	750	1.2	1.1	1.0
477	1.01	725	1.2	1.1	1.0
483	1.05	800	1.2	1.1	1.0
488	1.01	820	1.2	1.1	1.0
491	1.02	330	1.3	1.1	1.0

Metal Springs

Several springs are to be used in the probe for probe separation and instrument deployment. Therefore, the aging characteristics of these springs are of concern. Especially critical are the three springs to be used for separation of the probe from the spacecraft. These will be fabricated from Inconel and must be matched for force constant lest the probe be imparted with a tip-off error upon separation.

A survey of various spring manufacturers and the Spring Manufacturers Institute was conducted. All expressed the opinion that there would be no problem with relaxation or change in the force constant of the springs if they were properly designed (i. e., well within the elastic limit) and not subjected to excessive temperature or corrosion. However, no data were available to confirm this conclusion nor have any long-term reliability studies been done.

Discussions with the International Nickel Company, Inc., reaffirmed the statements of the spring manufacturers. Inconel alloys X-750 and 600 were recommended because of their resistance to relaxation at temperatures below 1200°F and 700°F, respectively. In addition, International Nickel provided a technical bulletin which gives data for the design and performance of high-nickel alloy springs[38].

Fig. 5, from the above publication, shows relaxation data as a function of stress and time for Inconel X-750 at elevated temperatures.

From these data, an activation energy of ca. 2.5 kcal/mole is obtained. By extrapolating the data given to 25°C, according to the equation

$$r = Ce^{-E/RT}$$

where: r = percent relaxation
E = activation energy
R = 1.99 cal/mole
T = absolute temperature, ^{o}K
C = constant

a relaxation value of 1.2×10^{-4}% is obtained. This value is considered to be insignificant.

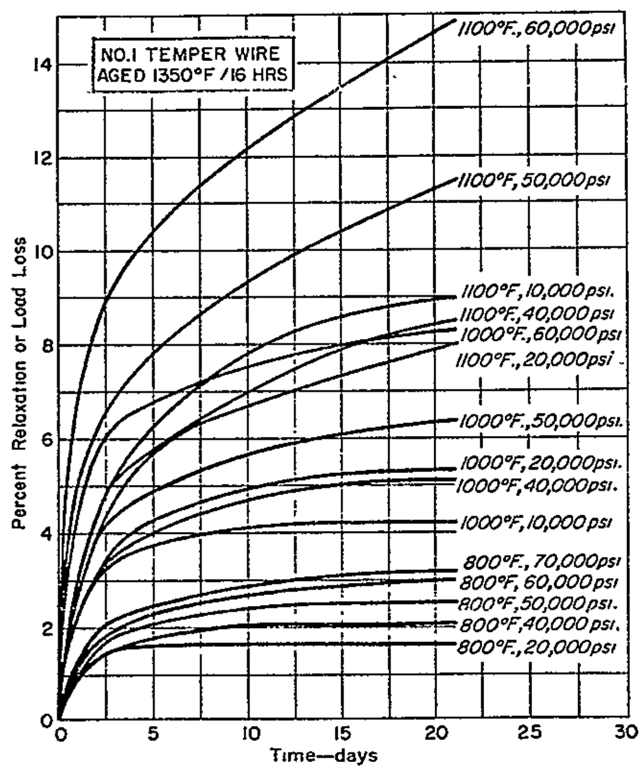

Fig. 5. Relaxation of Inconel X-750 Springs Made From No. 1 Temper Wire

These results are supported by Powell[39] in a study of compression springs for long-time operation in vacuum at $1000^{o}F$.

Beryllium-copper springs are proposed for use in one piece of instrumentation. The foregoing discussion for Inconel springs would also apply to beryllium-copper springs. In fact, one instrument manufacturer has stated that in 25 years they have never had a beryllium-copper spring

change calibration[40].

We conclude, therefore, that relaxation would not be a problem with springs, if they are properly designed and not subjected to corrosion or excessive temperature.

CONCLUSIONS

Predictions of mission reliability, based on a literature search and analysis, have revealed no major areas of concern for components of the outer planet atmospheric entry probe surveyed during this program. In a few cases, discussed below, these predictions are based on limited data and thus may be subject to error. In other cases, potential problem areas have been identified, resulting not from aging of a component but rather from a specific mode of construction or formulation, e.g., possible arcing of the MLI blanket.

In the following discussion conclusions of this survey are presented for each area of investigation:

Elastomers and Plastics

The extent of chemical degradation during a transit time of up to 8 years is not sufficient to alter properties of the materials surveyed during this program. Volatile additives may be present in certain elastomers and can be lost by evaporation, thereby affecting properties of the elastomer. The severity of this potential problem cannot be determined at this stage and will depend upon the function of the elastomer, the identity and vapor pressure of the additive and the effect of the additive on properties of the elastomer.

Thermal Control

No evidence was found to indicate that the thermoset resins, phenolics and polyurethane, would not perform as expected. Less information was available concerning the multilayer blankets; however, the data indicated that no significant degradation would occur due to exposure to deep space environments. A non-aging phenomenon was uncovered, related to the

MLI blanket, which should be considered during probe development. This concerns the possibility of arc-over in the MLI blanket with subsequent damage to the metal coating or plastic film.

Electronic Components

To a large extent the reliability of electronic components depends on part quality, usage, temperature cycling, environment, and transient suppression capabilities. Reliability can be enhanced by the selection of high reliability grade parts and extensive testing and screening before use. Generally, it appears that most components can be selected and screened to provide adequate reliability for an 8-year mission.

Pyrotechnic Devices

After accelerated aging equivalent to 8 years in space, no significant change in functional output parameters could be measured for the SBASI devices.

Metal Springs

Based upon a very limited amount of data and the consensus of all spring manufacturers contacted, there would appear to be no problem with aging of springs.

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